HYD 538

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EXPERIENCES OF THE BUREAU OF RECLAMATION WITH FLOW-INDUCED VIBRATIONS

Hydraulics Branch

Laboratory Report No. Hyd-538

DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
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CONTENTS

ABSTRACT

Difficulties encountered in USBR structures due to flow-induced vibrations show the need for recognizing that similar problems can occur elsewhere and indicate what measures can be taken to avoid or control them. Vibrations severe enough to interfere with operation and cause structural damage in several radial gate installations in canal check structures were caused by control shifting from the flexible bottom seals to the backing plates and back again. It was eliminated by redesigning the seals to produce a positive spring point. In Parker Dam Powerplant, serious turbine runner blade vibration was induced by vortex trails in the flow behind the blades. Tapering the trailing edges of the blades changed the frequency of vortex shedding and eliminated the resonant condition. At Grand Coulee Pumping Plant vibration in the steel portions of the discharge lines was greatly reduced by modifying the pumps to lower the magnitude of periodic impulses, and by stiffening the pipeline to avoid resonance and suppress circumferential and radial movements. Severe low frequency vibration or rhythmic surging in the Coachella Pipeline Distribution System was reduced to normal operational levels by changing the natural periods of system sections to avoid resonance, reducing the number of sections, and providing a snubbing action. Fluttering in overfalling nappes as at Black Canyon Dam was eliminated by splitting the jets so that full aeration occurs under the nappes.

DESCRIPTORS--*Vibrations/ *fluid flow/ radial gates/ gate seals/ vortices/ turbines/ turbine runners/ *resonance/ pumping plants/ aeration/ penstocks/ surges/ distribution systems/ pipelines/ flutter/ hydraulics/ crests/ check structures/ pumps/ *hydraulic structures/ hydraulic gates and valves/ drum gates/ reviews/ powerplants/ *corrections/ oscillation/ natural frequency/ damping/ low frequency/ impulses/ periodic variations/ nappe/ damages/

IDENTIFIERS--*Vortex trails/ vortex shedding/ splitters/ cyclic loading/ vibration control/ discharge lines/ hydraulic design/

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SUMMARY

A review is made of instances where vibrations induced by fluid flow phenomena have occurred in Bureau of Reclamation structures. A variety of experiences are cited including vibrations in radial gates, turbine runners, pumping plant discharge lines, an irrigation distribution pipeline system, and overfalling nappes. Remedial measures for eliminating or greatly reducing the vibrations included elimination or reduction of the driving forces, avoiding resonant conditions, stiffening the structures, and introducing additional damping.

INTRODUCTION

Vibrations induced in structures and equipment by earthquakes and by translatory or rotary motion of equipment are encountered so frequently in engineering work that another potent source of vibration--that of cyclic loadings induced by fluid flow--is often overlooked. The importance of this source, and the magnitude of the problems it can cause are manifested in such spectacular occurrences such as the wind-produced failure of the Tacoma Narrows Bridge in 1940, and in relatively minor wind-produced occurrences such as the rhythmic back and forth twisting of highway signs, sometimes to the point of failure. The mechanisms by which flowing fluids, both gaseous and liquid, generate vibration are treated in depth by Toebes.1/ Examples where flow-induced vibrations have caused significant engineering problems to the TVA are presented by Price.2/ This report presents similar experiences encountered by the Bureau of Reclamation.

1/Numbered references are listed in the Bibliography.

RADIAL GATES

Vibration of sufficient magnitude to cause operational difficulties, and even cracking in structural members, has occurred in several radial gate installations. In the cases where vibration occurred, the gates were discharging under differential heads of 5 or more feet, and backwater lay against the downstream side of the gate. Vibration was experienced only when gate openings were relatively small.

The Kings River check structure in the Friant-Kern Canal, Central Valley Project, California, was one of the first Bureau structures where vibration difficulty was reported. This check is at the entrance to an inverted siphon and is controlled by a radial gate 32 feet wide by 20 feet high. Vibration was first noticed in 1950; water depth was 8.09 feet on the upstream side of the gate, and about 3 feet on the downstream side. Under these head conditions, vibration occurred at an opening of 0.9 foot. The discharge was approximately 390 cubic feet per second. The vibration was characterized by significant upstream and downstream movement of the gate face between structural-steel members. Frequencies and amplitudes were not measured. The vibration was temporarily stopped by placing wooden wedges between the edges of the gate and the concrete walls, and water deliveries were made for several weeks with this makeshift, but effective arrangement.

Later in the irrigation season, with upstream heads varying from 11 to 12-1/2 feet over the canal invert, gate openings of 0.9 foot, and a discharge of 500 cubic feet per second, the vibration was much greater and could not be stopped by using wedges. The only successful remedial measure available at the time was to lower the water surface against the upstream face of the gate by lowering the water level in the canal. Sandbagging, jacking against one wall, unequal lifting of the gate to obtain a nonsymmetrical opening, and stressing the gate by tensioning a cable either laterally across the back of the gate, or vertically across it, were other measures that were tried with limited success.

In ensuing years, reports of vibration in a number of other radial gates were received. In some instances, conditions had been so severe that fracturing had occurred in secondary and even in primary structural members. One example is provided by Little Dry Creek check in the Friant-Kern Canal in California. During annual maintenance of the structure in 1960, the left gate of this three-gate check was found to be damaged (Figure 1A). Three of the 4- by 3/8-inch vertical tie bars were fractured, and the 12-inch WF beam second from the bottom was cracked through the entire web and through the downstream flange (Figures 1B and 1C).

Another example is provided by the Ringold wasteway turnout near Ephrata, Washington, where a 20-foot-wide by 22-foot-high radial gate suffered severe structural fractures from deflections of as much as one-fourth inch at a frequency of 5 cycles per second. The vertical movement was also severe and caused failure of one of the wire lifting ropes.

At the headworks structure in Black Canyon Main Canal, Idaho, 1/8-inch vibration amplitudes were measured in the 30-foot-wide by 10.5-foot-high radial gate. Frequency was of the order of 10 cps. Observers stated, "It appears that the horizontal beams vibrated in the fundamental mode in an upstream-downstream direction. Not all of the beams vibrate at any one gate setting, and at different settings different beams vibrate. At 0.83 feet opening there is not only the vibration in the I-beams but also an overall vertical vibration that is transmitted through the hoist cable and is noticeable in the movement of the reducing gears. There was no apparent shock transmitted through the arms to the pin bearing."

Analyses of these gate vibration problems led to a study of the seal geometry used at the bottom surface of radial gates (Figure 2, A and B). The pliable hollow music note seal could deflect easily under the water loads so that at relatively small openings the point of control, or spring point, on the gate could shift alternately from the deflected seal to the supporting steel immediately downstream. This rapid and continuous transfer of control point was believed capable of inducing the serious vibration experienced in the gate structures.

Several remedial designs were investigated on the gates at the Little Dry Creek check structure. All were based on the principle of establishing a well-defined control point on the bottom of the gate. In Gate No. 1 the music note seal was removed from the entire gate bottom except at the ends of the gate where a short length was retained for corner sealing. A 2- by 6-inch oak timber was bolted on the front of the skinplate with the lower edge of the wood extended three-fourths inch below the bottom of the gate. In Gate No. 2 the music note seal was removed from the entire length of the gate bottom and replaced by a 1/2-inch-thick steel plate 6 inches wide which extended 1/4 inch below the bottom of the gate. A 1/2- by 6-inch neoprene strip was cemented to the metal sealplate embedded in the concrete floor. In Gate No. 3, the music note seal was removed from the entire length of the gate, leaving the bottom of the gate to furnish contact with the sealplate. The metal sealplate in the floor was covered with a 1/2- by 6-inch-wide neoprene strip installed in the same manner as on Gate No. 2. The results were stated as follows: "The gates were tested when the canal was filled and no vibration was noted on any gate. It therefore appears that the requirement for a well-designed spring point was also fulfilled by the 2- by 6-inch oak timber used on Gate No. 1 and by the flange bottom of the skinplate of Gate No. 3, and also that fairly rigid rectangular rubber seal could be used successfully to replace the music note seal. Satisfactory sealing with the experimental modifications indicates the weight of the gate would be sufficient to seal with solid or rectangular rubber."

Subsequent to these and other field tests, all Bureau of Reclamation radial gate designs have included the fixed control point design (Figure 2C). This design consists of a relatively hard (60 to 70 Durometer) flat rubber seal about 5/8-inch thick that is clamped along the lower face of the gate. A small chamfer is provided on the rubber strip and forms the spring point that actually controls the flow of water.

Additional precautions are also taken. Relatively large holes are cut through the web of the bottom beam to allow flows of air or water to pass through the beam to relieve tendencies toward negative pressures beneath the beam. The holes are centered on the neutral axis of the beam, including the faceplate as part of the beam. Also, the lower half of the beam flange at the downstream end of the bottom I-beam is cut off and a bar of equivalent strength is added to the upper half of the flange. Heavier tie bars, consisting of channel sections, are used on the backs of the gates, and diaphragms are added under the channels between the bottom two or three beams. These design modifications have completely eliminated vibration and structural problems in radial gates under all operating conditions encountered, and are believed to obviate the vibration problem.

POWER AND PUMPING PLANTS

Flow-induced vibrations in hydro power and pumping plants have included water hammer in the penstocks or in the pump discharge lines, turbulent wakes downstream from runner blades, and surging in the draft tubes.3/ Under normal governor action during load changes, wicket gate movements may produce relatively rapid flow changes. The flow changes in turn produce rhythmic water-hammer pressure surges in the turbine penstock. An example of similar action in a 15-foot-diameter pump discharge line was found during a test program at Tracy Pumping Plant in California (Figure 3A).

In this case flow changes were made by means of a 108-inch butterfly valve. The frequency of the surges in cycles per second is defined by the familiar relationship:

$$F = \frac{a}{4L}$$

where

a = velocity of water-hammer wave travel in the conduit in feet per second, and

L = length of penstock in feet.

Fortunately, serious surging will rarely occur in a system because the pressure swings die out rapidly due to friction and to partial wave reflections from the partly opened gates. This decay is readily seen in Figure 3A. Resonance4/ can be, and usually is, avoided by analysis of penstock length and rate of change of waterflows by controlled governor responses.

More serious vibration problems have arisen due to periodically fluctuating loads induced on runner blades by vortex trails5/ (Figure 3B). This type of vibration has caused extensive cracking of blades in the 16-foot-diameter runners at Parker Dam on the lower Colorado River. Relationships determined by von Karman for vortex trails induced by water flowing past an immersed cylinder are shown in Figure 4A.6/ Symmetrical eddies, alternately clockwise and counterclockwise, form and then become detached from the downstream side of the cylinder. The result is an oscillating side thrust away from the last vortex. The frequency of oscillation, n, is contained in the Strouhal number, nD/v_o, which varies with Reynolds number as shown. In the Strouhal relation, D is a characteristic dimension such as the diameter, and v_o is the relative velocity of flow past the object.

At Parker Dam the natural frequency of the blades in water was nearly the same as the 65 cps frequency of the vortex trail computed for the 1.25-inch-thick trailing edges of the blades. Resonance is believed to have occurred to produce large flexures of the blades at a frequency of 55 cps, and ultimate cracking. The condition was corrected by tapering the trailing edges of the blades enough to raise the frequency of the vortex trail to a value where harmonic resonance would not occur (Figure 4B). A significant result of this runner modification was an increase in output of the units.

Surges in draft tubes can be a strong source of low frequency vibrations. The surges are periodic and occur in the draft tube water column of hydraulic turbines operating at partial gate openings.7/ The surging is caused by unstable vortices under the runner. In most cases the surging can be eliminated by the admission of air. Other cases have required baffles to break up the vortices. As these vortices form and are swept away, the pressure gradient beneath the runner changes. This produces a corresponding change in discharge through the turbine. Slight water-hammer effects then occur in the penstock, and add to the draft tube surges to create a further change in head on the turbine and variation in torque. Since the turbine is connected to the generator, electrical output varies and power swings occur. The magnitude of the power swings apparently depends upon the relation between the frequency of the draft tube surges and the natural frequency of oscillation of the generator-power transmission system. Serious operational difficulties could occur if resonance were possible, but this seldom occurs. Draft tube surging was experienced at the Parker Dam Powerplant, and measurements were made of draft tube pressure changes (Figure 5A). Similar low-frequency surging and vibration have also occurred at several other Bureau powerplants. Two of the methods used to control or prevent the problem include injection of air beneath the runner, and the installation of guide vanes in the draft tube. Much work remains to be done in this area to obtain a full understanding of the phenomenon, and thereby attain a complete solution.

Severe vibration of the exposed portions of the 12-foot-diameter Grand Coulee Pumping Plant discharge lines (Figure 5B) occurred when the units were first put into operation.8/ In some locations the measured displacement of the pipe shell was nearly one-half inch. Recordings of these vibrations and of the water pressure pulsations inside the pipe at the exposed sections (Figure 6, A and B) showed a basic frequency of 23-1/3 cps. This frequency was traced directly to the pump with the relation:

$$F = \frac{Nn}{60} = \frac{200(7)}{60}$$

where

N = speed of pump rotation, rpm and

n = number of blades.

The first step taken to reduce vibration was to reduce the driving force originating in the pump. This was accomplished by removing

12 inches from the leading edges of the five diffuser vanes and three-fourths inch from the seven impeller vanes to obtain more clearance between the impeller and the diffuser section, removing 20 inches from the tongue of the pump, and removing the splitter vane leading out of the pump (Figure 6C). The reduction in pressure pulsations at the pump are shown in Figure 6D, where the upper chart is for an unmodified pump, and the lower is for a modified unit.

The second step to reduce vibration was to stiffen the exposed sections of steel pipe. Originally these 12-foot-diameter sections were installed with stiffener ring anchor supports at 55-foot intervals (Figure 5B). Additional circular ribs fabricated from 8-inch H-bearing pile sections were bolted in place around the pipe on about 11-foot centers, and then securely welded to the pipe shell. The ribs proved effective due to increasing the natural frequency of the spans by adding structural dampings, by suppressing circumferential vibration of the pipe shell, and by preventing radial deflection patterns from carrying from one span to the next.

As a result of the pump modifications to reduce the forces initiating vibration and by stiffening the pipeline to reduce its tendencies to vibrate at the driving frequency, the vibrations were reduced to the point where many years of satisfactory service have been obtained without further distress.

PIPELINE DISTRIBUTION SYSTEMS

A cyclic surging sometimes occurs in pipe distribution systems provided with overflow pipe stands. In some cases, a periodic variation of flow or surge becomes so violent that it can prevent delivery of water. Trouble is especially apt to occur where the topography permits pipelines to run down the section lines with pipe stands at regular intervals. This is the arrangement on the Coachella distribution system in the Coachella Valley, California. The principal function of the pipe stands is to limit the static pressures in the line to relatively low values, and to prevent the large water-hammer pressures which could occur in a closed-conduit system. If the stands were not present, costs would be considerably higher because of the higher pressure pipe needed for the higher pressures encountered in a closed-conduit system.

The surges appeared as periodic variations of flow in a pipeline. The period of these changes ranged from about 60 to 100 seconds. In their most violent form the surges caused the pipe stands to be completely emptied when the waters receded, and overflowing when they returned (Figure 7A). In their mild form little could be observed other than a periodic increase and decrease in the depth of water flowing over the baffles. A profile sketch of a pipe stand system is shown in Figure 7B.

The first case investigated9/, 10/, 11/ was that of a single pipe reach between open pipe stands. The effects of the inertia of the water in the pipe reach, of frictional resistance to flow, and of changes of level, y, in the downstream half of the pipe stand at the upstream end of the reach, were accounted for. These individual reaches have natural periods of oscillation given approximately by the formula

$$T_n = 2\pi\sqrt{\frac{FL}{Ag}} \qquad (1)$$

where

F = water surface area in the downstream half of the pipe stand at the upper end of the reach
L = length of the reach
A = cross-sectional area of the pipe
g = acceleration of gravity

The oscillation caused variations of flow and a periodic rise and fall of the water level, y, in the upstream pipe stand.

If the flow coming into a reach is separated into two parts, consisting of a steady average flow, Q_o, and a superimposed sinusoidal variation, $q \sin \frac{2\pi}{T_o}(t)$, the sinusoidal variation will attempt to set the reach into oscillation at the incoming frequency. If the period of the incoming flow variation and the natural period of the reach are widely separated, the amplitude of the resulting oscillation will be small. However, as the period of the incoming flow approaches the natural period of the reach, resonance occurs and a resulting oscillation of large amplitude can be produced. Resonance in vibrating systems is well known, but in the pipe reach it produces a surprising result. Because the baffle in the pipe stand at the lower end of the reach acts as a weir and can therefore accommodate considerable flow variations with only minor changes of level, the flow variations induced in the reach are readily carried over it. Since resonance generates flow variations in the pipe reach greater than those fed into it, the reach behaves as an amplifier in the sense that the amplitude of the flow variation discharged at its lower end is greater than the amplitude coming into it. The ratio of the outgoing to the incoming amplitudes is controlled by friction, but the friction losses in pipelines are proportional to the square of the velocity, and at low flows friction is much reduced and amplification factors of six or more can be realized.

Although these amplification possibilities exist, a pipeline would still run without surging if no source of initiating oscillations were present. An attempt to find the most persistent of these sources by field observation proved fruitless because of the impossibility of seeing into the pipes when water was running in them. A laboratory model was therefore built and fitted with windows and transparent pipe sections which would permit such observations to be made (Figure 8A). The pipe stands were constructed of 20-inch-diameter steel pipe fitted with sheet metal baffles with adjustable crests. These pipe stands were connected by 125-foot lengths of 8-inch-diameter pipe which had 180° bends at midlength so that the pipe stands could be grouped together. Plexiglass windows in the pipe stands permitted observers to see into the interior below water level. At the upper end of the system a half stand was attached to a head box so the wall of the head box took the place of the baffle. Water was pumped into this head box and entered the model by flowing into the half stand. A plunger, operated by a variable speed motor, provided a means of surge initiation. A length of transparent pipe was inserted in the 8-inch-diameter line at the half stand as shown in Figure 8B.

After watching the flow conditions in the transparent pipe, the mechanism of the auto-oscillation which initiated the most persistent of the field surges became apparent. The nappe falling over the baffle carried air with it as it plunged into the pool on the downstream side of the pipe stand. This air appeared as bubbles. Some of these floated back to the surface, but part were carried into the pipe. These soon rose to the top of the pipe and collected into a long bubble. The end of this long bubble is seen in Figure 8B. Because the pipe slopes, this long bubble tends to float back up into the pipe stand but is opposed by the impact of the water coming into the pipe from the pipe stand. However, as the bubble grows, the bouyant force grows with it and finally part of the bubble blows back into the pipe stand. The volume vacated by the air is immediately filled with water whose kinetic energy delivers an impulse to the system and initiates an oscillation of small amplitude. This oscillation has the natural period characteristic of the reach. The velocity changes associated with the oscillations influence the time when the next blowback will occur. Observation shows that this occurs at a time in the cycle which will permit energy to be fed into the oscillation. The accumulation and release of air thereafter lock into step with the oscillation and feed enough energy into it to maintain it at a small amplitude.

Although this type of auto-oscillation is of too small amplitude to cause any trouble in the reach in which it originates, it does supply a periodic change which can be amplified to a surge of unmanageable size in succeeding reaches. Surges can also be initiated by the transient oscillations set up by making or cutting off deliveries and in other ways. At any rate, experience seems to indicate that small amplitude surges are always present. Even the forces produced by winds blowing across the tops of open pipe stands seem to be capable of causing small initiating oscillations which can be amplified progressively in the lower reaches.

A number of proposals were studied in the model for eliminating or greatly reducing the surging problem. These included adding friction to obtain greater damping; air vents to reduce surge initiation; and baffle crest changes, siphons, and gates that reduced the effects of weir flows. None of these was successful. However, excellent results were obtained when airtight covers were placed over some of the stands. Field tests substantiated their effectiveness.

An analytical study of the effect of the covers was first attempted on a system with two pipe reaches having the common pipe stand covered, as shown in Figure 7B. This analysis was carried to the point where it became possible to compute the natural periods. Two periods were found. Also evident was the enormous work required to analyze systems with several covers. An electric analog device was then worked out to shorten this phase of the investigation. In this analog an electric current represented a flow of water in the hydraulic system. A voltage change represented a rise or fall of a water level, an inductance represented the inertia factor, and an electrical resistance represented the hydraulic friction loss. Readout was by means of an oscillograph or an oscilloscope.

A system comprising n pipe reaches with n - 1 covered pipe stands between, and parts of the two open pipe stands at the upstream and downstream ends, had n characteristic modes of vibration and each had its own natural period. Such a system will therefore resonate if an oscillation having a period near to any one of the natural periods is imposed upon it. However, only the mode having the longest period will ordinarily resonate strongly enough to be of importance. It also appeared that a system created by capping pipe stands will resonate less freely than the individual pipe reaches which existed before the pipe stands were capped. Another discovery, which permits an important simplification of what would otherwise be a complicated situation, is that in the mode with the longest period all the pipe reaches have velocities which swing in unison. It is therefore permissible, as an approximation, to treat the whole system as an individual pipe reach for which Eq (1) takes the form

$$T = 2\pi\sqrt{\frac{F}{g}\sum\frac{L}{A}} \qquad (2)$$

where the summation sign indicates that the quotients, $\frac{L}{A}$, for each of the pipe reaches in the system are to be added together.

An explanation of how the covers produce stabilization also came from these analog studies. The action is threefold. Briefly, they (1) change the natural periods so that the systems can be thrown out of phase, (2) they reduce the number of systems capable of resonance, and (3) they replace the original reaches with the systems which resonate less freely.

The covers do not completely eliminate surges, but effectively and economically hold the surges within manageable limits. They have been in use in the field for a number of years and, with appropriate vents and vacuum control units in them, are a thoroughly proven means of surge control in this type of distribution system.

An interesting but unplanned feature is their ability to pass a heavy surge induced by an outside source, and then resume normal operation. When some moss screens became plugged and were abruptly removed for cleaning, the sudden increase of flow initiated a surge of sufficient amplitude to lift some of the covers. Most of the covers reseated themselves and became airtight again. Another incidental advantage accruing from their use is the elimination of accumulations of trash resulting from unwanted objects being tossed into the open pipe stands.

SPILLWAYS AND SPILLWAY GATES

An interesting and undesirable flutter or oscillation has occurred in sheets of water, or nappes, falling over certain spillway gates and spillway crests. The Bureau's first significant experience with this problem occurred at Black Canyon Dam in Idaho and was investigated in 1939. The flutter was characterized by a periodic upstream and downstream velocity component superimposed upon the normal parabolic path of the sheet of water. The fluttering did not cause noticeable movement of the gates or of the dam itself, but rattled windows and doors in homes and structures hundreds of yards away.

Black Canyon Dam is a concrete gravity section and has a three-bay spillway located near the left abutment (Figure 9A). Drum gates 64 feet long by 14 feet 6 inches high are used to control the quantities of water released. When maximum flows are required through the spillway, the gates are fully lowered and the top surfaces of the gates act to complete the normal surfaces of the ogee crest (Figure 10A). When no flow is desired, the gates are raised by rotating them around hinges at their upstream corners to the extent needed so overtopping will not occur (Figure 10B). When controlled rates of flow are desired, the gates are positioned so that water may pass over the downstream lips and fall freely to the concrete surfaces below (Figure 10C). During this type of operation with certain specific depths of water present over the gate lips, fluttering occurred (Figure 9B).

Investigations made with accelerometers, pressure cells, and suitable recording equipment showed that fairly small accelerations occurred on the gates at frequencies ranging from 7 to 18 cycles per second. The maximum pressure fluctuations exerted on the dam and gates were 8.7 pounds per square foot, or about 0.06 pounds per square inch. The fluctuations occurred when the reservoir water surface was from 0.22 to 1.45 feet above the lips of the gates. The higher vibration frequencies were always associated with the greatest depth of water, and the lowest frequencies with the shallowest depths of water over the gates. Also, the fluctuations were only present when the gates were at openings between 30 to 70 percent. Examination of Figure 10C will show that in this range of openings a significant free fall occurs from the gate lips to the surfaces below. At smaller openings the fall to the concrete chute is relatively small, and at larger openings the water falls onto the gates themselves.

The possibility of resonance occurring between the dam and the fluttering nappes was of interest. Attempts were made to determine the natural frequency of the dam by setting off small charges of dynamite and recording the movement of the dam on accelerometers. Blasts made at ground level were unsuccessful for several reasons, including the fact that shockwaves were freely transmitted through the air to affect the accelerometers. Somewhat better results were obtained with underwater blasts in the reservoir 800 feet upstream from the dam. However, results were inconclusive because the frequencies of about 25 cps recorded were near the natural frequency of the instruments in use at the time (1939).

The fluttering at Black Canyon Dam was stopped by splitting the overfalling jets so air could enter freely beneath them. For test purposes, a 6- by 8-inch timber, 6 feet long, was held in place against the downstream edge of Gate No. 1 by ropes so the nappe was widely split (Figure 9C). If the timber was located offcenter near one end of the 64-foot-long gate, only the portion of the flow from the split to the nearest pier stopped fluttering (Figure 9D). The longer portion of flow apparently did not receive sufficient air and continued to flutter. When the 64-foot-long sheet of water was split in the center, both sides ceased to flutter (Figure 9C).

Similar flutter occurred on Prosser Diversion Dam in Washington. This low concrete dam backs up the river to make diversions possible, and most of its length consists of spillway sections which operate freely whenever overtopped. No gates are used. In cross section, the crest profile is seen to terminate abruptly at a short vertical face a short distance downstream from the high point of the crest (Figure 11). Water falls freely through the air on a trajectory path from this lip. Air vents 15 inches in diameter were provided in the piers to aerate the nappe, and the piers were about 200 feet apart.

Shortly after completion of the dam in 1956, flows at depths of 0.5 to 0.7 foot occurred. In spite of the air vents provided in the piers, fluttering was noted in the nappes. This fluttering caused air vibrations that rattled doors and windows in homes and commercial buildings as far away as 1,000 feet.

In a manner similar to that found effective at Black Canyon Dam, splitters consisting of 8- by 8- by 1/2-inch angles were mounted so they extended horizontally downstream from the crests (Figure 11B). Spacings of about 33 feet were used and all of the flutter at the Prosser Creek structure was effectively stopped.

On the basis of these experiences, and the experiences of other domestic and foreign groups, a basic cause of the fluttering is apparently inadequate admission of air under the nappe. Usually the problem can be cured by splitting the nappes at intervals not greater than perhaps 35 feet, so that adequate air admission can take place. Such splitters are now commonly used on gates and crests wherever the problem is likely to be encountered.

CONCLUSION

The foregoing examples of difficulties encountered in engineering structures due to flow-induced vibrations show the need for recognizing that similar problems might occur whenever and wherever fluid flows exist. Present day Bureau designs are profiting from these hard-learned lessons. Significant in this regard is the new Canadian River aqueduct in Texas. The aqueduct has a 140-mile-long main pipeline 5 to 6 feet in diameter and is constructed with occasional open pipe stands to limit maximum head and allow use of relatively inexpensive concrete pipe. Surging similar to that encountered in the Coachella Distribution System is inherent in the basic design. However, through lessons learned in the Coachella investigation, the Canadian River aqueduct is being designed to control surging to relatively small magnitudes, so maximum economy and trouble-free service are obtained. Similar care will be taken on the basis of present knowledge to avoid or control flow induced vibrations in future structures. The knowledge gained through future experiences will also be utilized and will be made available to the engineering profession.

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Figure 1
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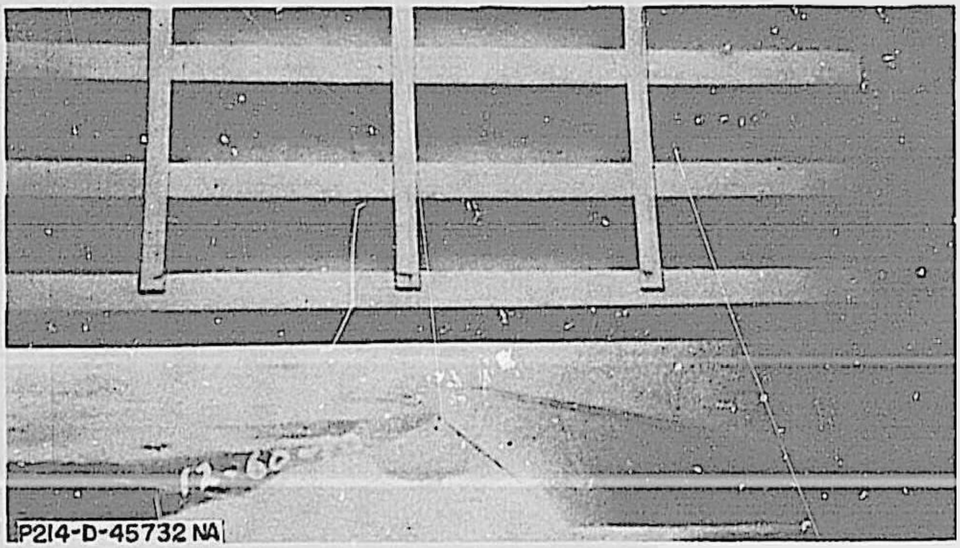
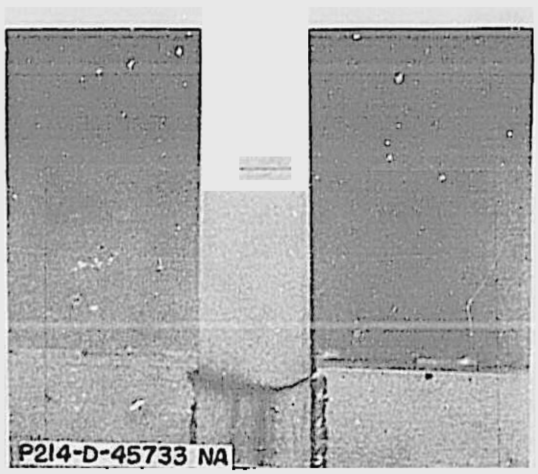
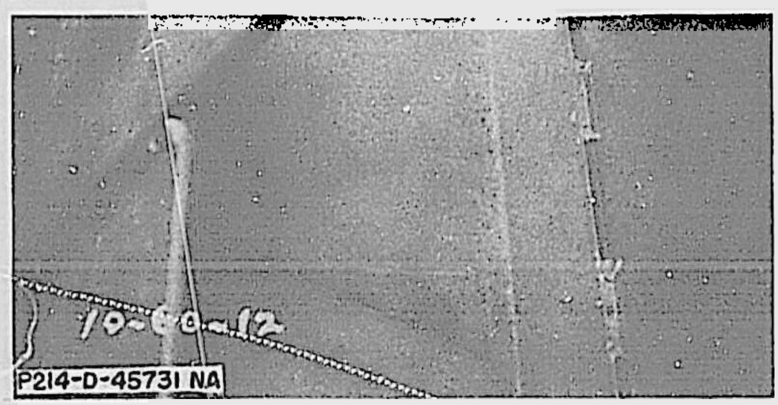


A. Downstream face of radial gate.



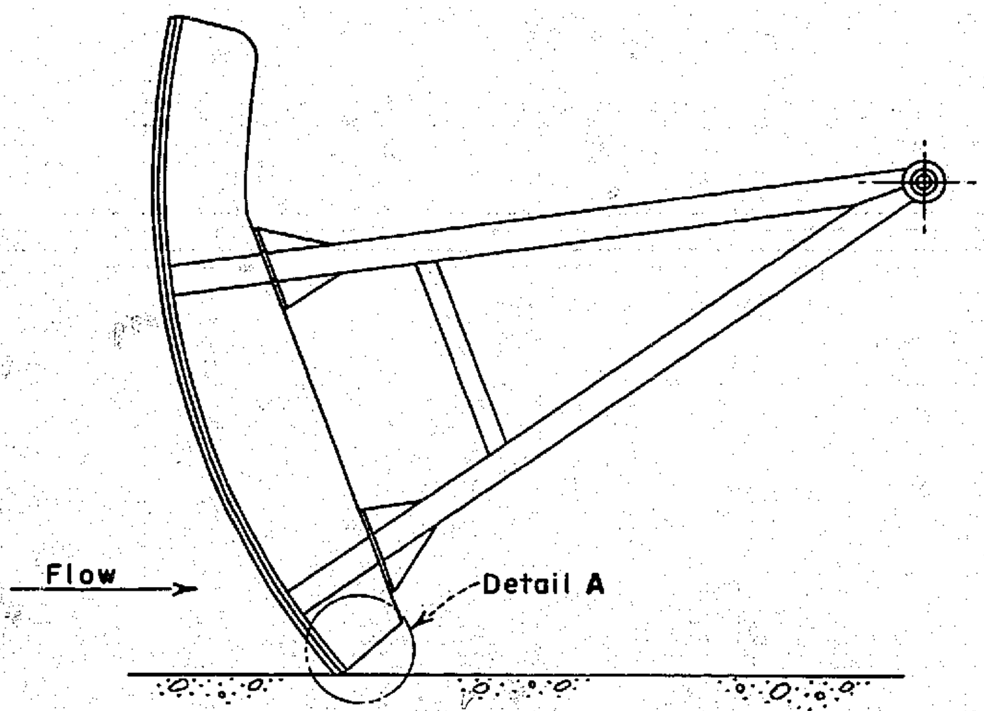
B. Typical cracking through three of the 4- by 3/8-inch vertical tie bars.



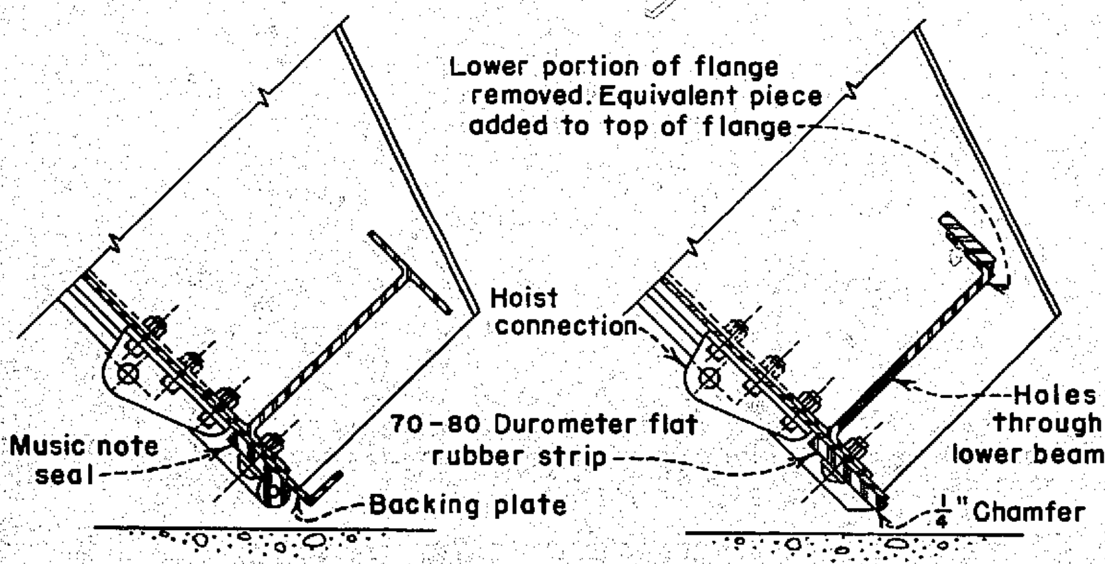
C. The second from the bottom 12-inch WF beam was cracked through the web and downstream flange.

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES

Vibration-Induced Cracking in Left Gate of Little Dry Creek Check--Friant Kern Canal, California

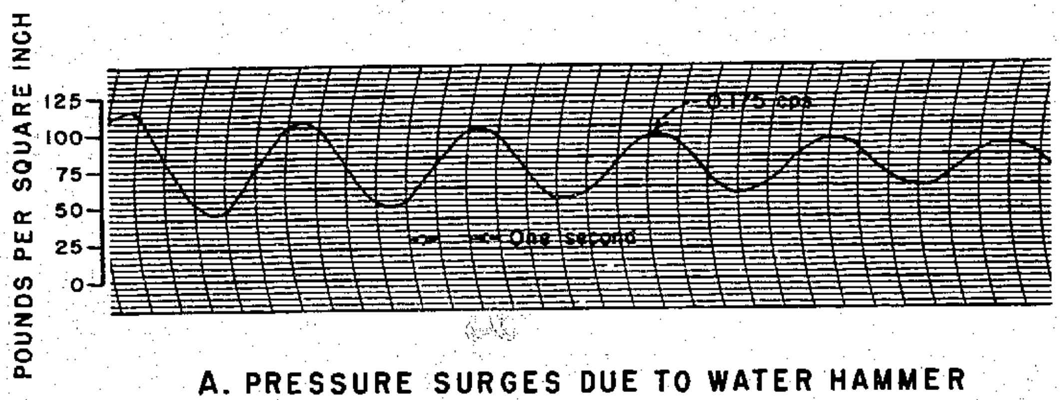


A. TYPICAL RADIAL GATE

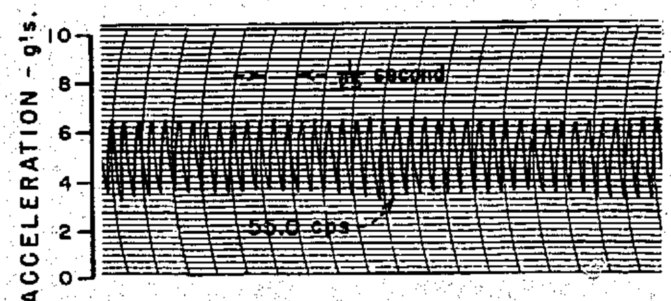


B. DETAIL A - INITIAL DESIGN   C. DETAIL A - REVISED DESIGN

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES
INITIAL AND REVISED BOTTOM SEALS ON RADIAL GATES

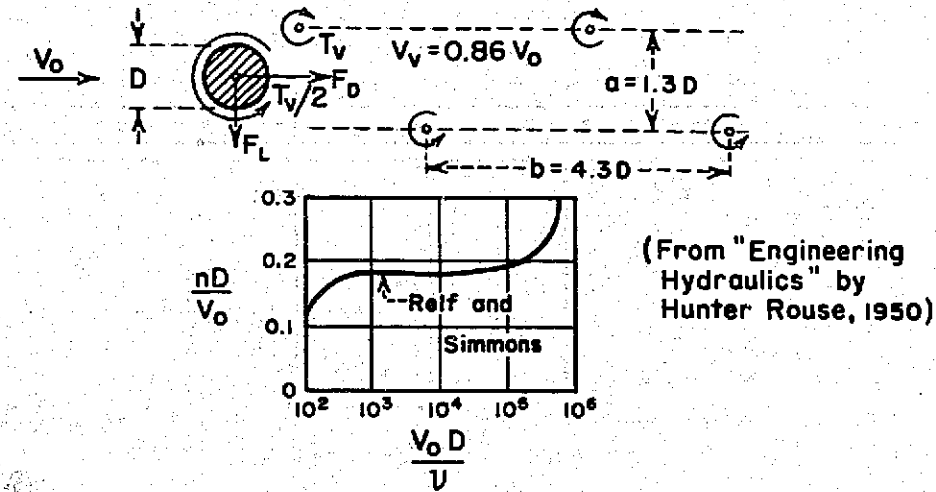


A. PRESSURE SURGES DUE TO WATER HAMMER
TRACY PUMPING PLANT
L = 5130 FT.
V = 3600 FT. PER. SEC.

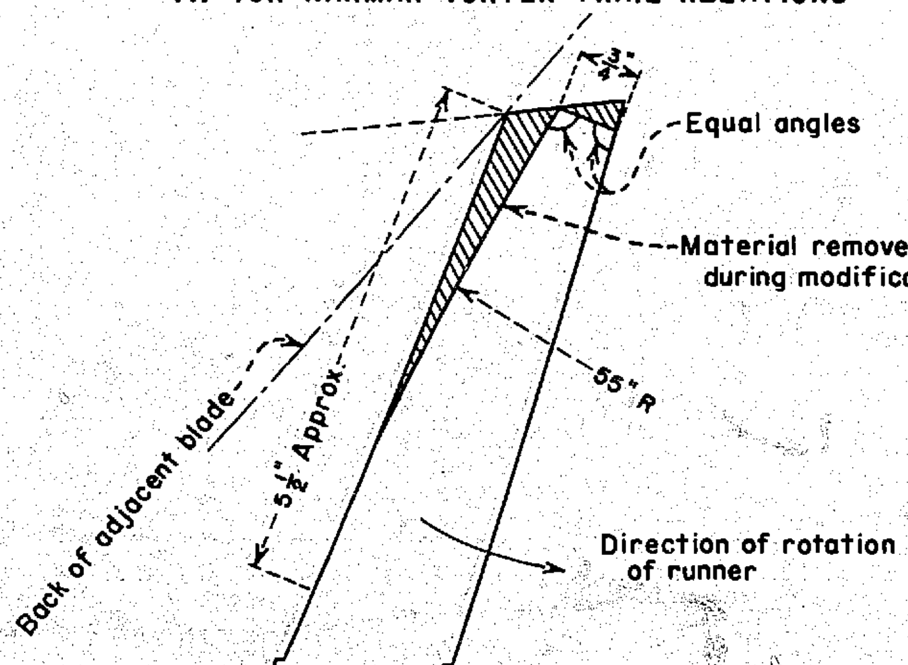


B. TRANSVERSE ACCELERATIONS OF TURBINE RUNNER
UNIT NO. I BLADE NO. 2
PARKER POWER PLANT
(0.8 GATE POSITION)

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES
PENSTOCK PRESSURE SURGES, AND TURBINE RUNNER VIBRATIONS
HYDRO POWER PLANTS



A. VON KARMAN VORTEX TRAIL RELATIONS

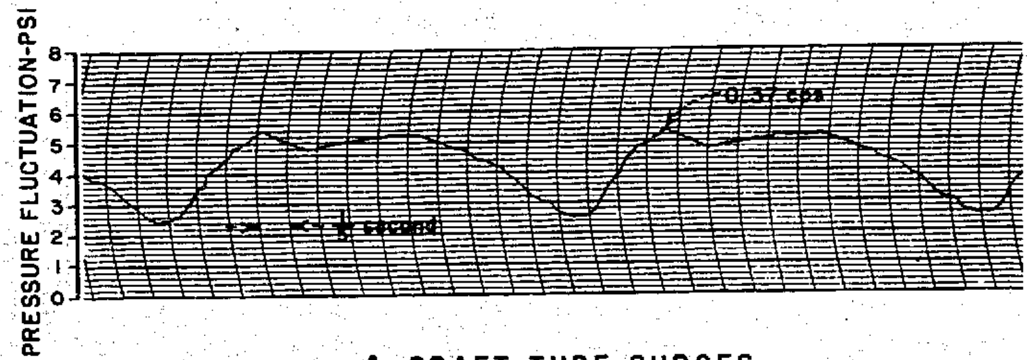


B. CROSS SECTION OF TRAILING EDGE AND MODIFICATION OF TURBINE BLADE

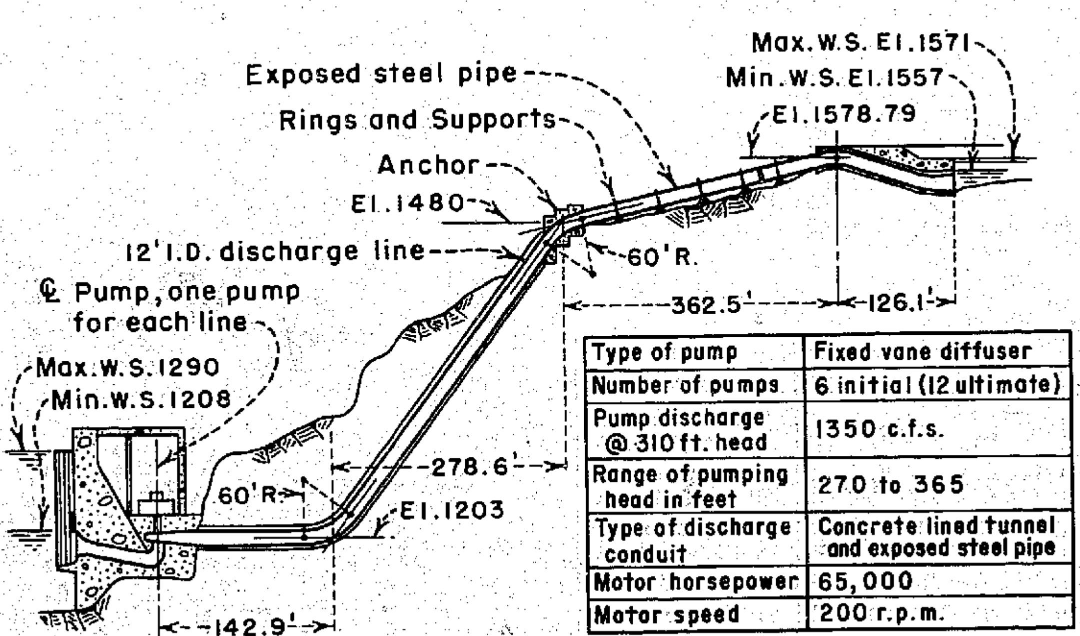
FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES

VON KARMAN VORTEX TRAIL RELATIONS, AND TURBINE RUNNER BLADE MODIFICATIONS

HYDRO POWER PLANTS



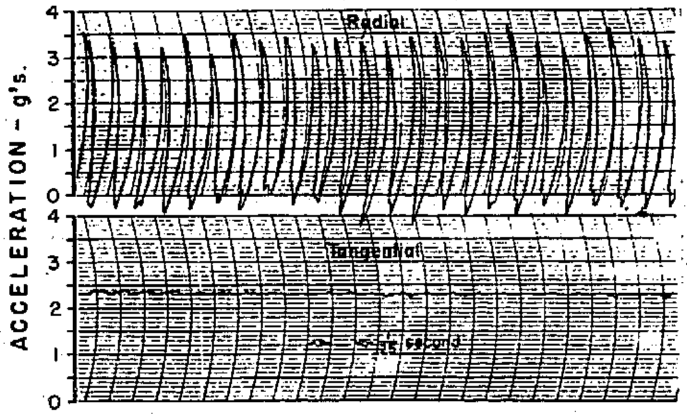
A. DRAFT TUBE SURGES
UNIT NO.1, PARKER POWER PLANT
N = 94.7 R.P.M. (0.50 GATE POSITION)



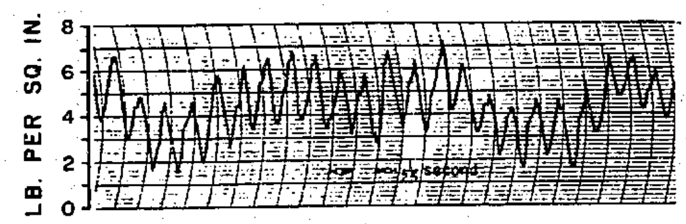
Type of pump	Fixed vane diffuser
Number of pumps	6 initial (12 ultimate)
Pump discharge @ 310 ft. head	1350 c.f.s.
Range of pumping head in feet	270 to 365
Type of discharge conduit	Concrete lined tunnel and exposed steel pipe
Motor horsepower	65,000
Motor speed	200 r.p.m.

B. TYPICAL SECTION THROUGH GRAND COULEE PUMPING PLANT AND DISCHARGE LINES

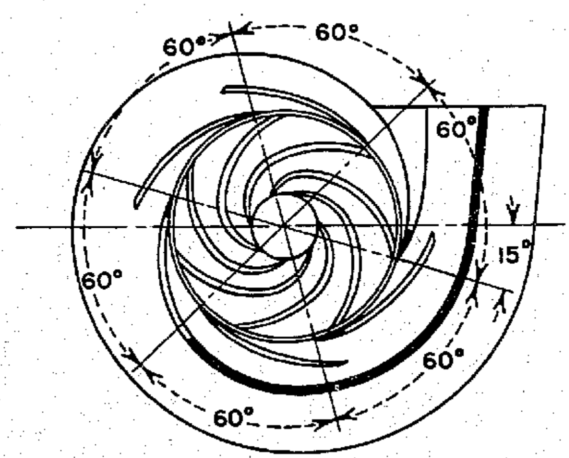
FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES
DRAFT TUBE SURGES AT PARKER POWER PLANT AND PROFILE OF GRAND COULEE PUMPING PLANT



A. RADIAL AND TANGENTIAL ACCELERATIONS OF PIPE SHELL

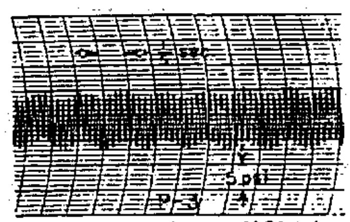


B. PRESSURE PULSATION AT EXPOSED SECTIONS OF PUMP-DISCHARGE LINE

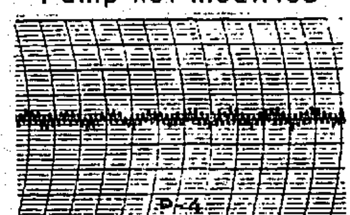


Shaded areas indicate the location and amount of material removed by the modification.

C. MODIFICATION OF PUMP P-4 TO REDUCE PRESSURE PULSATION



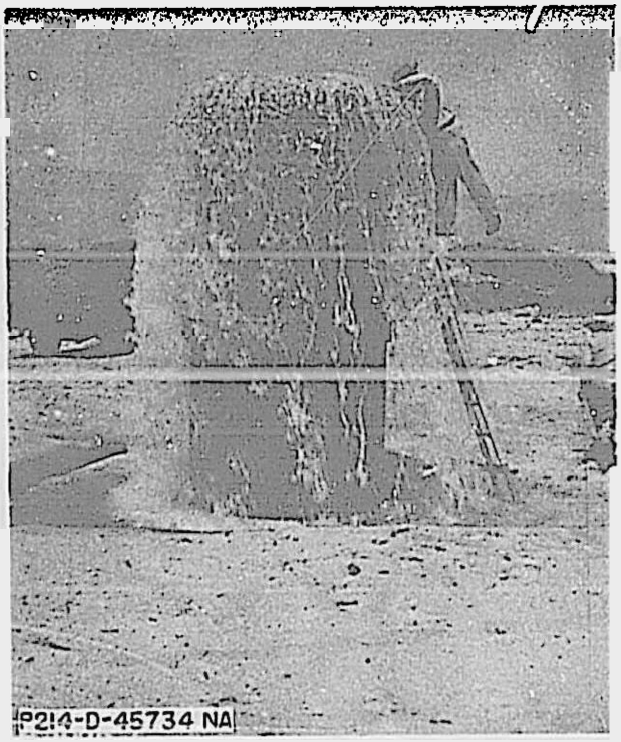
Pump not modified



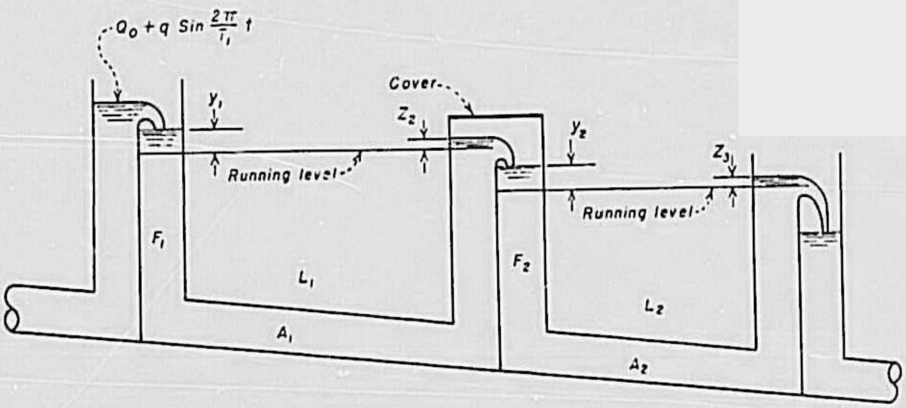
Modified pump

D. PERIODIC SURGE AT DISCHARGE OUTLET. UNITS P-3 AND P-4

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES
PRESSURES, ACCELERATIONS, AND PUMP MODIFICATIONS AT GRAND COULEE PUMPING PLANT



A. Pipe stand overflowing due to surging in pipeline system.

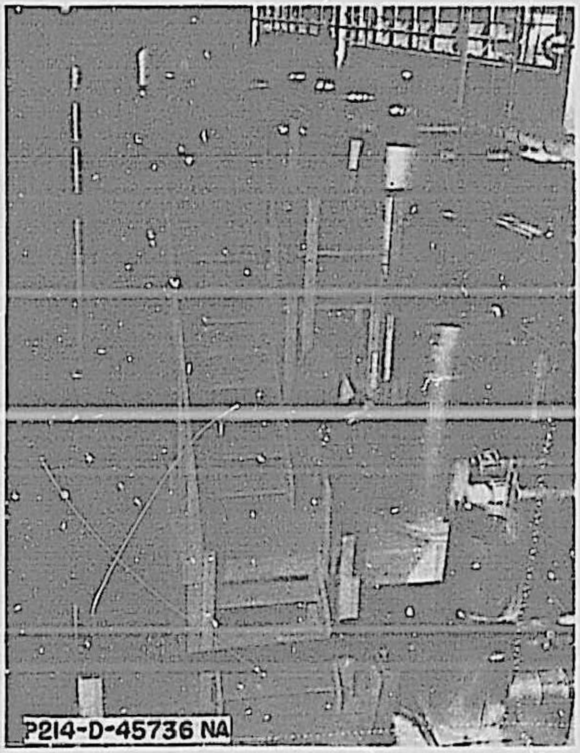


B. Schematic view of pipeline system, with two reaches having common stand covered.

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES

Surging in Pipeline Distribution System and Profile of Pipe Stand System

Figure 8
Report Hyd-538

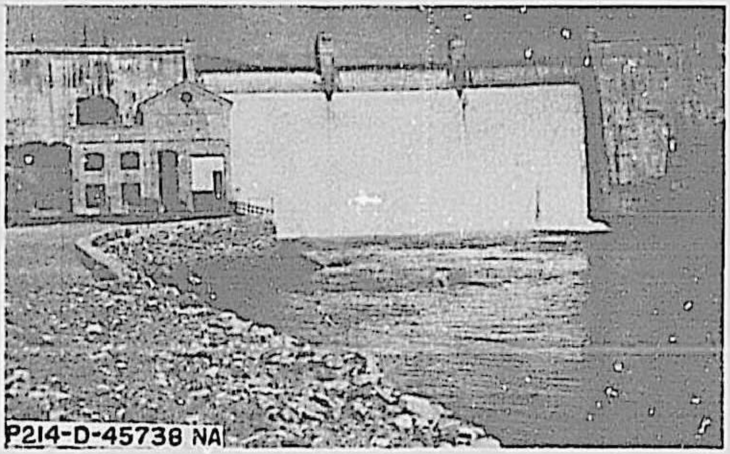


A. Laboratory model of distribution system.

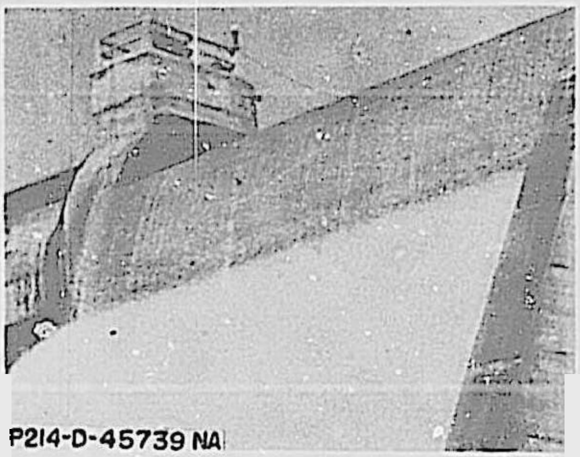
B. Air bubble entrapped in transparent pipe section just downstream from a pipe stand.

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES

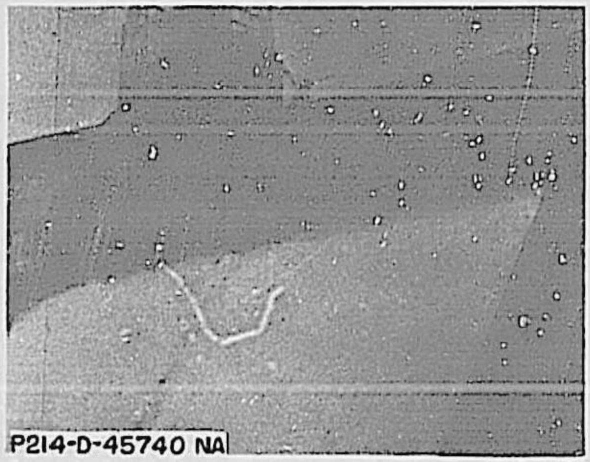
Laboratory Model of a Pipe Stand Distribution System and Flow in Pipeline Near a Stand



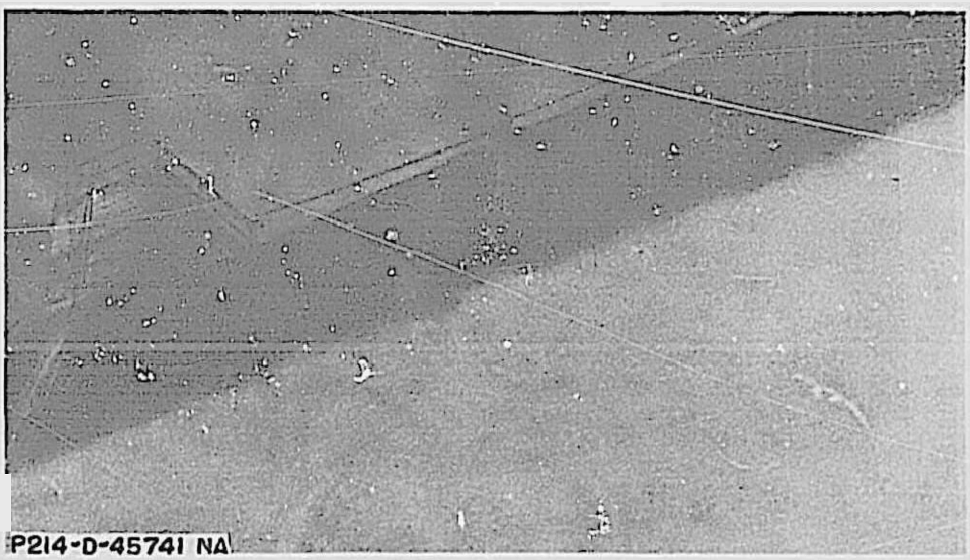
A. Black Canyon Dam Spillway.



B. Fluttering nappe with 0.4-foot head.



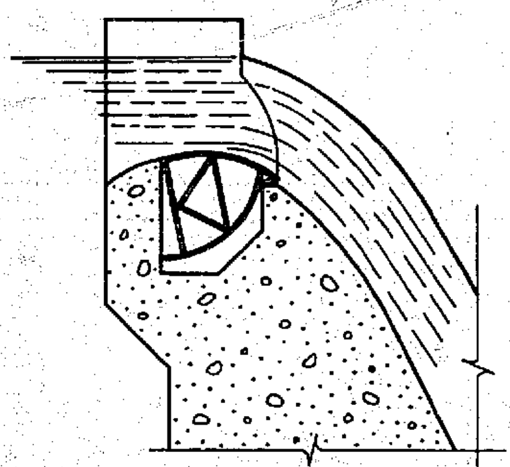
C. With log at one-third point on 64-foot gate flutter persists in wide portion of nappe.



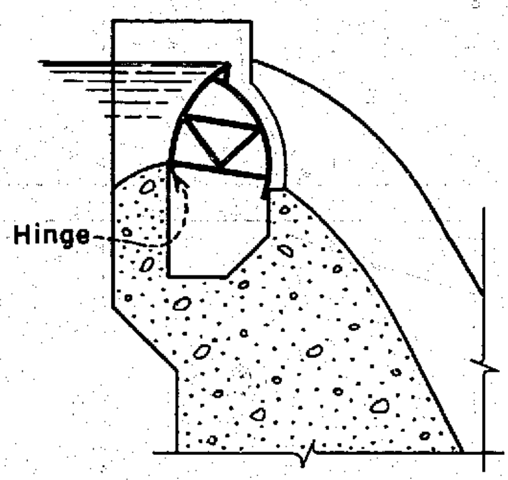
D. With log (splitter) in center of 64-foot-long gate, all flutter is eliminated. Head = 0.4 foot.

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES

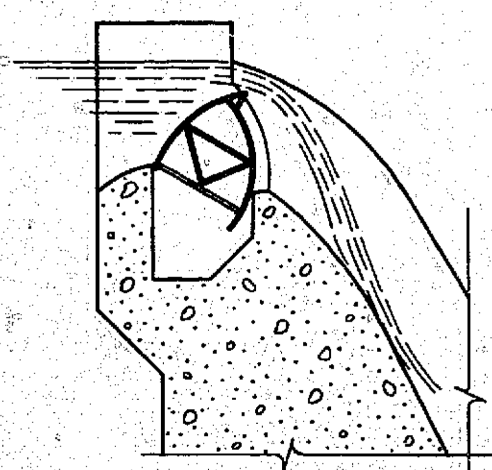
Fluttering Nappe on Black Canyon Dam Spillway
Idaho



A. DRUM GATE FULLY LOWERED. MAXIMUM FLOW.

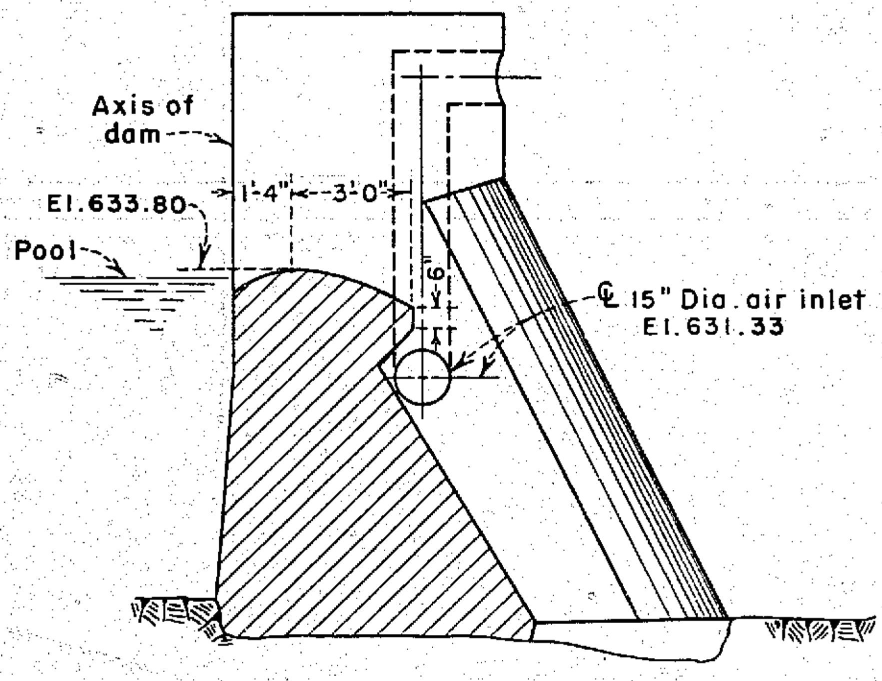


B. DRUM GATE FULLY RAISED. NO FLOW

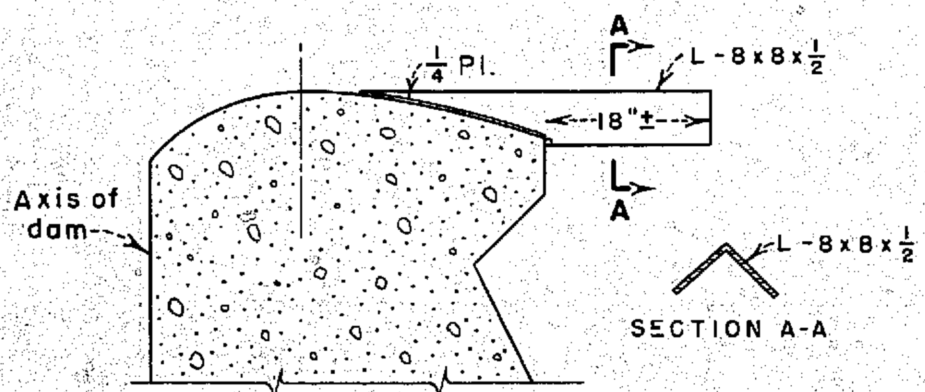


C. GATE PARTIALLY RAISED WITH FLOW PASSING OVER LIP. CONDITION WHERE FLUTTER OCCURS.

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES
DRUM GATES ON BLACK CANYON DAM — IDAHO



A. CREST, DIVIDING PIER, AND ORIGINAL AIR VENTS



B. SPLITTERS ADDED TO INCREASE AERATION BENEATH THE NAPPE

FLOW-INDUCED VIBRATIONS IN USBR STRUCTURES

CREST SHAPE AND SPLITTERS USED ON PROSSER DIVERSION DAM — WASHINGTON

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7-1750
(10-64)

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table 1

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03 (exactly)*	Square centimeters
	0.092903 (exactly)	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	9,463.58	Cubic centimeters
	0.946358	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.02903* (exactly)	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

ABSTRACT

Difficulties encountered in USBR structures due to flow-induced vibrations show the need for recognizing that similar problems can occur elsewhere and indicate what measures can be taken to avoid or control them. Vibrations severe enough to interfere with operation and cause structural damage in several radial gate installations in canal check structures were caused by control shifting from the flexible bottom seals to the backing plates and back again. It was eliminated by redesigning the seals to produce a positive spring point. In Parker Dam Powerplant, serious turbine runner blade vibration was induced by vortex trails in the flow behind the blades. Tapering the trailing edges of the blades changed the frequency of vortex shedding and eliminated the resonant condition. At Grand Coulee Pumping Plant vibration in the steel portions of the discharge lines was greatly reduced by modifying the pumps to lower the magnitude of periodic impulses, and by stiffening the pipeline to avoid resonance and suppress circumferential and radial movements. Severe low frequency vibration or rhythmic surging in the Coachella Pipeline Distribution System was reduced to normal operational levels by changing the natural periods of system sections to avoid resonance, reducing the number of sections, and providing a snubbing action. Fluttering in overfalling nappes as at Black Canyon Dam was eliminated by splitting the jets so that full aeration occurs under the nappes.

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Hyd-538
Simmons, W. P.
EXPERIENCES OF THE BUREAU OF RECLAMATION WITH FLOW-INDUCED VIBRATIONS
USBR Laboratory Report No. Hyd-538, Hydraulics Branch, September 1964. Bureau of Reclamation, Denver, 14 pp., 11 Figures, 11 References, 1964

DESCRIPTORS--*Vibrations/ *fluid flow/ radial gates/ gate seals/ vortices/ turbines/ turbine runners/ *resonance/ pumping plants/ aeration/ penstocks/ surges/ distribution systems/ pipelines/ flutter/ hydraulics/ crests/ check structures/ pumps/ *hydraulic structures/ hydraulic gates and valves/ drum gates/ reviews/ powerplants/ *corrections/ oscillation/ natural frequency/ damping/ low frequency/ impulses/ periodic variations/ nappe/ damages/

IDENTIFIERS--*Vortex trails/ vortex shedding/ splitters/ cyclic loading/ vibration control/ discharge lines/ hydraulic design/

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